

# Characterizing the Lyman-alpha forest

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## **Abstract**

Using a sample of 3376 quasar spectra from the Sloan Digital Sky Survey we fit the flux distribution function assuming a lognormal density distribution and photoionization equilibrium. From this we derive new constraints on the mean optical depth, equation of state, and variance of the density field as a function of redshift.

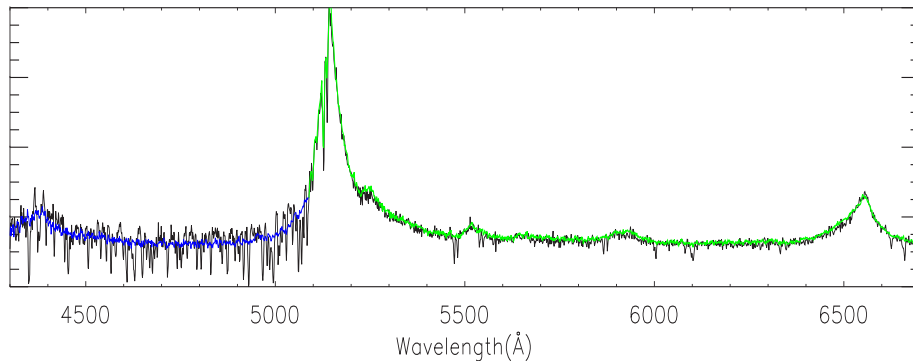
# The life of a wave packet

1. Quasars emit a broad spectrum of photons (oversimplified at left by a flat spectrum except for  $\text{Ly}\alpha$  emission in the vicinity of the quasar itself). The photons redshift as they travel through the expanding universe.
2. Photons of wavelength  $\lambda = 1215.67 \text{ \AA}$  are readily absorbed by neutral hydrogen (the  $\text{Ly}\alpha$  transition). As the spectrum of photons passes through the intergalactic medium, photons with  $\lambda = 1215.67 \text{ \AA}$  in the frame of the gas are scattered.
3. When we finally measure the spectrum on earth, we see a band of many  $\text{Ly}\alpha$  absorption lines called the **Lyman alpha forest**.

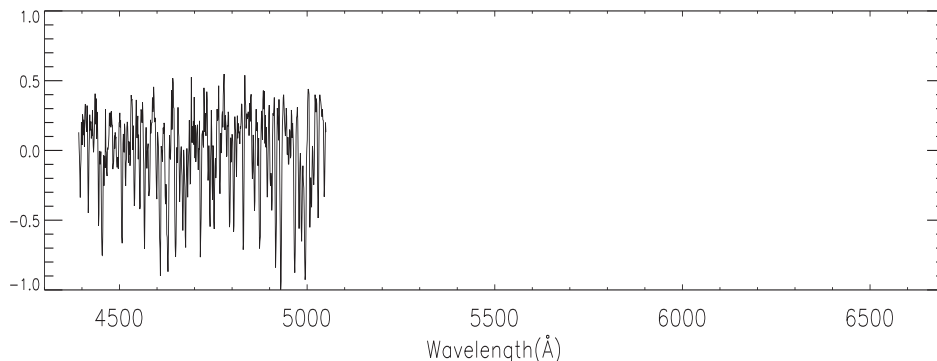
[Missing from this slide is the accompanying animated figure]

# Our normalization procedure

Each spectrum is initially processed by the SDSS Pipeline [Frieman *et al.* & the SDSS team, 2002]. We then normalize each spectrum relative to an estimate of a “mean spectrum” based on knowledge of the entire sample [Burles *et al.*, in preparation]. This method is complementary to direct optical depth measurements using true continuum normalization [Bernardi *et al.*, 2002].



Spectra are fit using a PCA technique in the region redward of the quasar Ly $\alpha$  emission [green curve]. This fit is then used to predict the normalization [blue curve] in the Ly $\alpha$  forest.

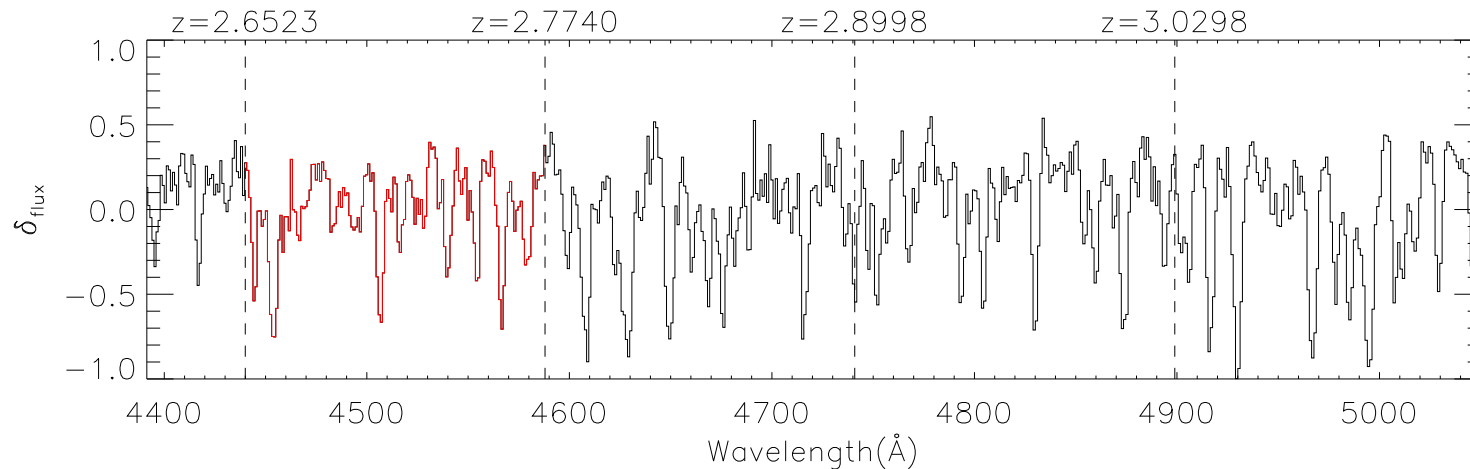


Resulting normalized flux in the Ly $\alpha$  forest:

$$\delta_{\text{flux}} = \frac{\text{starting spectra (black)}}{\text{predicted norm (blue)}} - 1$$

# Slicing each spectrum into redshift bins

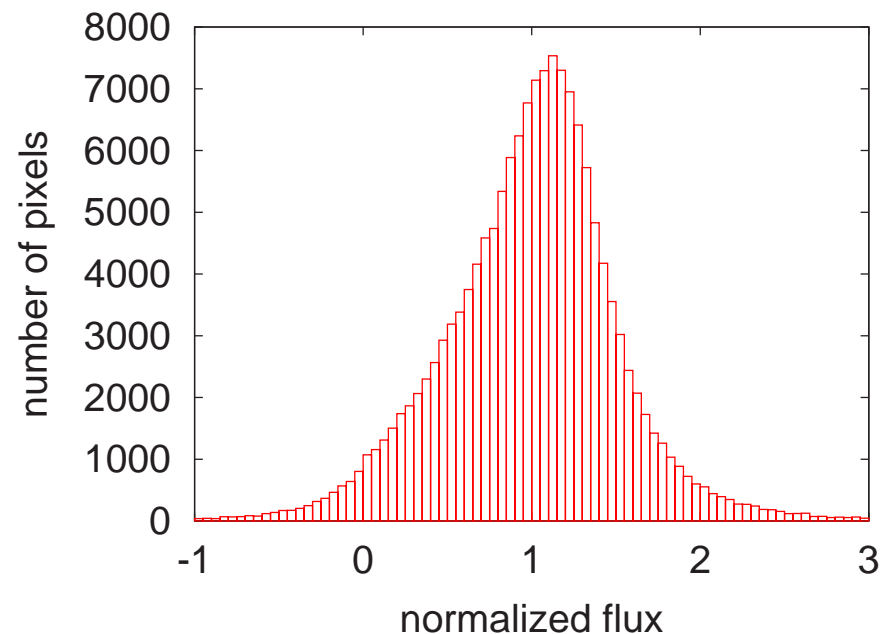
- We next separate the pixels of each spectrum into bins corresponding to  $\text{Ly}\alpha$  absorption by the intergalactic medium in different redshift shells.



- For example, the pixels in the region between the first two dotted lines, shown in red in the above  $\text{Ly}\alpha$  forest spectrum, correspond to  $\text{Ly}\alpha$  absorption in the redshift range  $z = 2.65$  to  $z = 2.77$ . Note that this redshift is not the redshift of the quasar, but rather the redshift of the intervening absorber.
- Using this method we chop each spectra into sets of pixels belonging to each of 18 different redshift bins in the range  $z = 2.1$  to  $z = 4.4$ . Thus, in the end, each redshift bin has pixels from many different spectra.

# Determining the flux distribution function

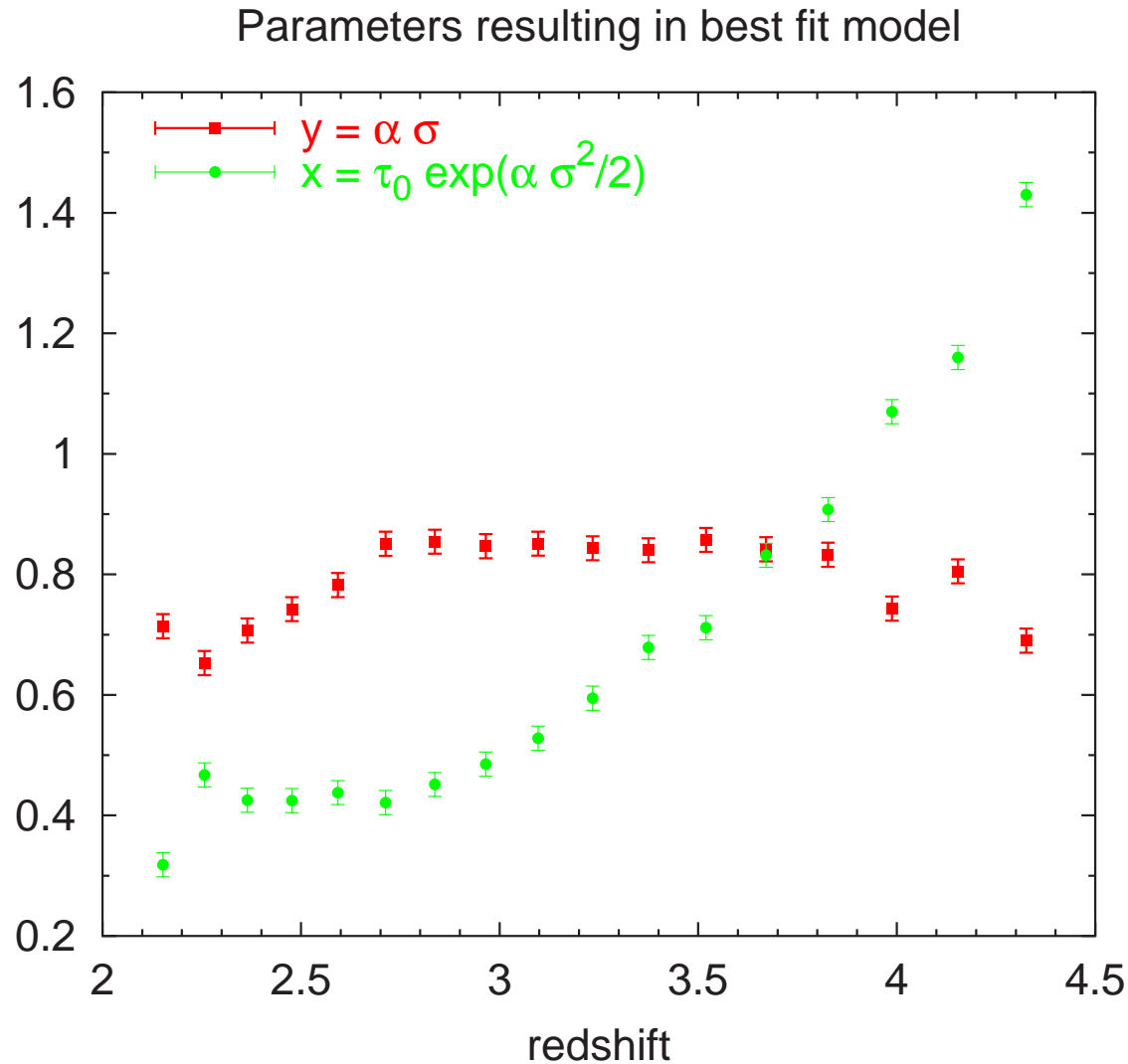
- The distribution of fluxes measured in a set of pixels is a crude measure of the Ly $\alpha$  optical depth, and thus the dark matter density field, at that redshift.
- The **flux distribution function (FDF)** results from histogramming the set of flux points in each redshift bin.
- At right is an example of one such histogram, from the redshift bin  $2.65 < z < 2.76$  (containing  $10^5$  pixels).
- Our goal is to find a model for the observed flux resulting from a distribution of density fluctuations in the IGM that correctly reproduces the FDF of the data.



# Modeling the flux distribution function

- Following many before us [Bi & Davidsen, 1997; Nusser & Haehnelt, 1999], we model the dark matter density field as a lognormal distribution in  $\rho/\langle\rho\rangle$  (with variance  $\sigma$ ).
- Assuming photoionization equilibrium, the optical depth  $\tau$  resulting from this density field is found from the mean optical depth  $\tau_0$  and the parameter  $\alpha$ :
$$\tau = \tau_0 \left( \frac{\rho}{\langle\rho\rangle} \right)^\alpha$$
- The normalized flux  $F$  in each pixel is determined from the optical depth:
$$F = \frac{e^{-\tau}}{\langle e^{-\tau} \rangle}$$
- For each set of pixels, points are randomly drawn from this flux distribution and then noise is added that correctly mimics the noise in the real data.
- Since the three parameters in the model ( $\sigma$ ,  $\tau_0$  and  $\alpha$ ) are degenerate, only two constraints can be derived from the data. We choose to work with the two combinations  $y \equiv \alpha\sigma$  and  $x \equiv \tau_0 \exp(\alpha\sigma^2/2)$ .

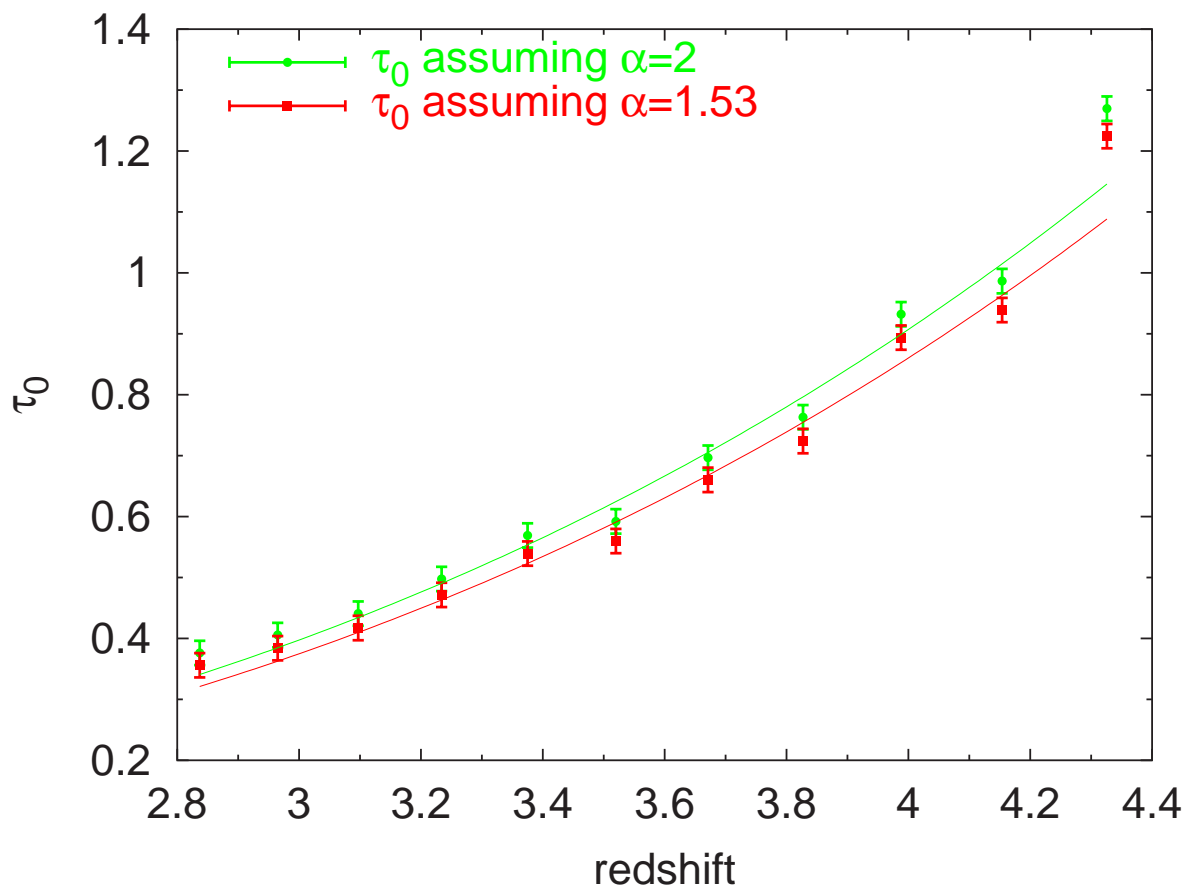
# Results



- We determine the best fit to the FDF at each redshift bin by finding values of the parameters  $x$  and  $y$  which minimize  $\chi^2$ .
- The error is estimated by repeating this procedure on separate subsets of the data.

# Redshift dependence of the mean optical depth $\tau_0$

The equation of state parameter  $\alpha$  should fall in the range  $\alpha = 2$  (isothermal) to  $\alpha = 1.53$  (ideal gas). Evaluating the curve on the previous slide for these values of  $\alpha$  gives our best estimate of the mean optical depth  $\tau_0(z)$ :



Our best fit power-law is overplotted (solid curves).

- For  $\alpha = 2$ :

$$\tau_0(z) = 0.0024(1 + z)^{3.7}$$

- For  $\alpha = 1.53$ :

$$\tau_0(z) = 0.0021(1 + z)^{3.7}$$



This work was done in collaboration with Professor Scott Burles (MIT) and is still in progress. Please contact [kburgess@mit.edu](mailto:kburgess@mit.edu) with further questions or to receive a copy of the preprint once available.

The Sloan Digital Sky Survey (SDSS) is a joint project of The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Princeton University, the United States Naval Observatory, and the University of Washington. Apache Point Observatory, site of the SDSS telescopes, is operated by the Astrophysical Research Consortium (ARC). Funding for the project has been provided by the Alfred P. Sloan Foundation, the SDSS member institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is <http://www.sdss.org/>.